Power System Security

S. Chakrabarti
Outline

Introduction

Major components of security assessment

On-line security assessment

Tools for contingency analysis
  DC power flow
  Linear sensitivity factors
  Line outage distribution factor

Algorithm for contingency analysis
What is power system security?

Power system security may be looked upon as the probability of the system’s operating point remaining within acceptable ranges, given the probabilities of changes in the system (contingencies) and its environment.
Dy Liacco first pointed out in 1967 that a power system may be identified to be operating in a number of states.

![Diagram of Operating States of the Power System](image-url)
Preventive state

- The preventive state is actually the normal state. The term ‘preventive’ was used to stress the ‘Security’ aspect of the normal operation.

- Normal operating condition usually means that all the apparatus are running within their prescribed limits, and all the system variables are within acceptable ranges.

- The system should also continue to operate ‘normally’ even in the case of credible contingencies. The operator should ‘foresee’ such contingencies (disturbances) and take preventive control actions (as economically as possible) such that the system integrity and quality of power supply is maintained.
Emergency state

- The power system enters an emergency state when some of the components operating limits are violated; some of the states wander outside the acceptable ranges, or when the system frequency starts to decrease.
- The control objective in the emergency state is to relieve system stress by appropriate actions.
- Economic considerations become secondary at this stage.
Restorative state

- Restorative state is the condition when some parts (or whole) of the system has lost power.
- The control objective in this state is to steer the system to a normal state again by taking appropriate actions.

Fink and Carlson further refined the model of power system states, as shown in Fig. 5.2.

Power system operation can be described by three sets of generic equations: one differential, and two algebraic. Of the two sets of algebraic equations, one comprises of equality constraints, which is the balance between generation and load demand. The other set consists of inequality constraints which ensure that the various components in the system and the states (e.g. voltages and currents) remain within safe or acceptable limits.

The match between generation and load is the fundamental prerequisite for normal operation of the system. Also, the generator and transformer loads should not exceed the rated values, and the transmission lines should not be loaded beyond their capacities. In the normal state, the system also has some amount of spinning reserve to ensure a degree of security.

If the generation falls below certain threshold, load increases beyond some limit, or a potentially dangerous disturbance becomes imminent, the system is said to enter the alert state. 

\[ E \Rightarrow \text{Equality constraint} \]
\[ I \Rightarrow \text{inequality constraint} \]
\[ - \Rightarrow \text{Negation (violation)} \]
Power system operation can be described by three sets of generic equations: one differential, and two algebraic.

Of the two sets of algebraic equations, one comprises of equality constraints (E), which is the balance between generation and load demand.

The other set consists of inequality constraints (I) which ensure that the various components in the system and the states (e.g. voltages and currents) remain within safe or acceptable limits.
If the generation falls below certain threshold, load increases beyond some limit, or a potentially dangerous disturbance becomes imminent, the system is said to enter the alert state.

Though the equality (E) and inequality (I) constraints are still maintained, preventive controls should be brought into action to steer the system out of the alert state.

If preventive control fails, or the disturbance is reverse, the system may enter into an emergency state, though the demand is still met by the generation, one or more component or state violate the prescribed operation limits. Emergency control actions should immediately be brought into action to bring the system back to the normal state.
If the emergency control actions also fail, the system may enter extremis state which is characterized by disintegration of the entire system into smaller islands, or a complete system blackout.

It may take anywhere between few seconds to few minutes for a system to enter an extremis state from a normal state.

The restoration process however is very slow. It may take several hours or even days to bring the system back to normal.
Major components of security assessment

▶ System monitoring
▶ Contingency analysis
▶ Preventive and corrective actions
System monitoring

- The prerequisite for security assessment of a power system is the knowledge of the system states. Monitoring the system is therefore the first step.

- Measurement devices dispersed throughout the system help in getting a picture of the current operating state. The measurements can be in the form of power injections, power flows, voltage, current, status of circuit breakers, switches, transformer taps, generator output etc., which are telemetered to the control centre.

- Usually a state estimator is used in the control centre to process these telemetered data and compute the best estimates of the system states.

- Remote control of the circuit breakers, disconnector switches, transformer taps etc. is generally possible. The entire measurement and control system is commonly known as supervisory control and data acquisition (SCADA) system.
Contingency analysis

Once the current operating state is known, the next task is the contingency analysis. Results of contingency analysis allow the system to be operated defensively. Major components of contingency analysis are:

- Contingency definition
- Contingency selection
- Contingency evaluation
Contingency analysis...contd.

- Contingency definition involves preparing a list of probable contingencies.
- Contingency selection process consists of selecting the set of most probable contingencies in preferred; they need to be evaluated in terms of potential risk to the system. Usually, fast power flow solution techniques such as DC power flow are used to quickly evaluate the risks associated with each contingency.
- Finally, the selected contingencies are ranked in order of their security, till no violation of operating limits is observed.
Preventive and corrective actions are needed to maintain a secure operation of a system or to bring it to a secure operating state. Corrective actions such as switching of VAR compensating devices, changing transformer taps and phase shifters etc. are mainly automatic in nature, and involve short duration. Preventive actions such as generation rescheduling involve longer time scales. Security-constrained optimal power flow is an example of rescheduling the generations in the system in order to ensure a secure operation.
On-line security assessment

- In earlier days, security assessment in a power system was mainly offline in nature. Predefined set of rules or nomographs were used to assist the operators in the decision-making process.

- However, due to the highly interconnected nature of modern power systems, and deregulated energy market scenarios, operating conditions and even the topology of a power system changes frequently. Off-line techniques for security assessment are therefore no longer reliable in modern power systems.

- On-line security assessment techniques use near-real-time measurements from different locations in a power system, and continuously update the security assessment of the system.
Active power flow between buses $i$ and $j$ is given by,

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\theta_i - \theta_j)$$ (1)

Assuming $V_i = V_j = 1$ p.u., and $\sin(\theta_i - \theta_j) \approx (\theta_i - \theta_j)$, (since $(\theta_i - \theta_j)$ is usually very small),

$$P_{ij} \approx \frac{(\theta_i - \theta_j)}{X_{ij}}$$ (2)

Power injection at bus $i$ therefore is given by,

$$P_i = \sum_{j=1}^{N} P_{ij} = \sum_{j=1}^{N} \frac{(\theta_i - \theta_j)}{X_{ij}}$$ (3)
DC power flow... contd.

Hence,

\[
\frac{\partial P_i}{\partial \theta_i} = \sum_{j=1}^{N} \frac{1}{x_{ij}} \quad (4)
\]

\[
\frac{\partial P_i}{\partial \theta_j} = -\frac{1}{x_{ij}} \quad (5)
\]

Now,

\[
\Delta P_i = \frac{\partial P_i}{\partial \theta_1} \Delta \theta_1 + \ldots + \frac{\partial P_i}{\partial \theta_N} \Delta \theta_N \quad (6)
\]

Iterative equations for power flow then become:

\[
\begin{bmatrix}
\Delta P_1 \\
\vdots \\
\Delta P_N \\
\end{bmatrix}
= 
\begin{bmatrix}
B_{11} & B_{12} & \ldots & B_{1N} \\
\vdots & \ddots & \ddots & \vdots \\
B_{N1} & B_{N2} & \ldots & B_{NN}
\end{bmatrix}
\begin{bmatrix}
\Delta \theta_1 \\
\vdots \\
\Delta \theta_N
\end{bmatrix}
\quad (7)
\]

Or,

\[
\Delta P = [B][\Delta \theta] \quad (8)
\]
Linear sensitivity factors

- Analyzing in details a large number of contingencies is a difficult task.
- An easy (approximate) way to quickly compute any possible violation of operating limits is the one of linear sensitivity factors.
- Two such sensitivity factors for checking line flow violations are generation shift factors and line outage distribution factors.
Generation shift factors

They calculate the effect of change in generation on the line flows, as shown below:

$$a_{li} = \frac{\Delta f_i}{\Delta P_i}$$  \hspace{1cm} (9)

where $a_{li}$ is the linearized generation shift factor for the $l$th line for a change in output of $i$th generator; $\Delta f_i$ is the MW change in power flow in the $l$th line; $\Delta P_i$ is the change in generation at the $i$th bus.
It is assumed here that the change in generation at the $i$th bus is picked up by the reference bus. The new values of power flows in each line can be found from:

$$f^\text{new}_l = f^\text{old}_l + a_{li} \Delta P_i; \quad \forall l = 1, 2, \ldots, L$$  \hspace{1cm} (10)

where $f^\text{old}_l$ is the power flow in the $l$th line before the $i$th generator went out. Assuming $P^\text{old}_i$ to be the output of the $i$th generator before fault, above equation can be expressed as,

$$f^\text{new}_l = f^\text{old}_l - a_{li} P^\text{old}_i; \quad \forall l = 1, 2, \ldots, L; \quad [\because \Delta P_i = -P^\text{old}_i].$$  \hspace{1cm} (11)
Once the new values of flows are computed for all the lines, they are compared with corresponding line flow limits. Operators are ‘alarmed’ in case of any limit violations.

In a practical power system, due to governor actions, the loss of generation at the bus $i$ may be compensated by their generators throughout the system.

A frequently used method is to assume that the loss of generation is distributed among participating generators in proportion to their maximum MW rating.
Therefore, the proportion of generation pickup by the $j$th generator is given by,

$$\gamma_{ji} = \frac{P^\text{max}_j}{N_G \sum_{k=1}^{N_G} P^\text{max}_k}$$  \hspace{1cm} (12)$$

where $P^\text{max}_k$ is the maximum MW rating of the $k$th generator; $N_G$ is the number of participating generators; $\gamma_{ji}$ is the proportionality factor for pickup on generating unit $j$ when unit $i$ fails.

The new line flows are then given by,

$$f_i^{\text{new}} = f_i^{\text{old}} + a_{li} \Delta P_i - \sum_{j=1, j \neq i}^{N_G} (a_{li} \gamma_{ji} \Delta P_i)$$  \hspace{1cm} (13)$$

Note: It is assumed here that no unit hits its generating limit.
Line outage distribution factors are used to quickly check line overloading as a result of outage of any transmission line, and are defined as follows:

\[ d_{lk} = \frac{\Delta f_l}{f_{old}^k} \]  \hspace{1cm} (14)

where \( d_{lk} \) is the line outage distribution factor for line \( l \) after an outage of line \( k \); \( \Delta f_l \) is the change in MW flow in line \( l \) due to the outage of line \( k \); \( f_{old}^k \) is the flow in line \( k \) before its outage.

The new value of line flow is given by,

\[ f_{l}^{new} = f_{l}^{old} + d_{lk} f_{k}^{old} \]  \hspace{1cm} (15)
Algorithm for contingency analysis

Start

Obtain existing system information from State Estimation

Prepare the list of contingencies

$c = 1$

$l = 1$

Compare the new line flows $f_{i}^{new}$ for generator or line outages

$l = l + 1$

$\frac{f_{i}^{\text{min}}}{f_{i}} \leq f_{i}^{\text{new}} \leq \frac{f_{i}^{\text{max}}}{f_{i}}$

No

Display warning

Yes

$l = L$

No

$c = c + 1$

Yes

$c = C$

Yes

End

$L =$ No. of lines

$C =$ No. of selected contingencies